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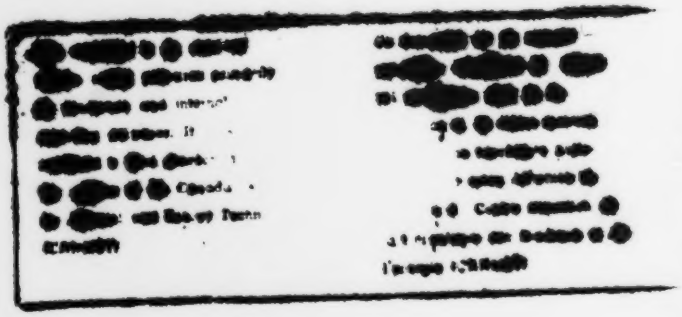

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DEVELOPMENT OF IMPACTOR SIZE SELECTIVE DUST SAMPLERS AT THE ELLIOT LAKE LABORATORY

G. Knight*

ABSTRACT

The Elliot Lake Laboratory has designed and used impactor size selectors for respirable and other dust samplers both in the laboratory and in mines. Their advantages have been compact size, reproducibility of size selection performance–based on the high precision of drill manufacture and use, flexibility in design and layout and easy manufacture in a machine shop.

The major problems in design and performance have been:- secondary deposition of dust and overloading with coarse dust. Secondary deposition modifies the calculated size selection and either limits the spacing between adjacent orifices or orifices and other features or requires a final calibration against a reference sampler. However, as the match between an impactor size selector and a respirable dust specification is not perfect the calibration is desirable. Overloading of the coarse dust deposition zone leads to changes in size selection characteristics as the dust load increases giving a definite limit to acceptable dust collection quantities. The use of multiple stages increases the dust holding capability manyfold. All the dust samplers developed at the Elliot Lake Laboratory have used two or more successive stages to increase dust holding capacity.

KEYWORDS: Gravimetric sampling; size selective sampling; dust sampling; impactor size selectors; personal samplers; high volume samplers; size distribution sampling train;

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INTRODUCTION

Size selective sampling to simulate the separation of airborne dust in the human lungs into two or more fractions is now the usual procedure when assessing airborne dust with any relationship to the potential health hazard. This is followed by gravimetric or other analyses of the dust collected on the filter. In hard rock mines free silica is the component of the dust which is often the most significant potential health hazard. The Elliot Lake Laboratory has developed a sampling and analysis procedure for routine use in hard rock mines termed– CAMPEDS(1,2). This procedure collects dust using a size selective personal sampler with three assessments of dust:-

1. gravimetric assessment of the total respirable fraction (TRD).
2. X-ray diffraction assessment of the quartz(free silica) component of the respirable dust fraction(RQD).
3. the assessment of the combustible components by weighing before and after ashing(RCD), and its corollary the ash or mineral fraction.

This technique was first carried out using a commercially available cyclone size selector and filter holder– the CASELLA personal sampler(3,4). The 10mm nylon cyclone, widely used in North America, was not chosen because it collected less dust spread over a larger area giving a substantially less sensitivity for the direct-on-filter quartz analysis technique. Following a suggestion by a USBM colleague the use of an impactor size selector was investigated(5,6). This led to the development of a simple, compact size selector and filter holder which was much smaller and lighter than the Casella cyclone(1,2).

The paper by Marple and McCormack(7) led to rethinking the concept and combined with the much improved pumps available for personal sampling led to the development of a four litre/minute personal sampling pump. At the same time there was a requirement for a high flow rate size selective sampler for use underground and a maximum flow rate sampler for use with 47 mm diameter filters was also developed for sampling long lived radionuclides with size segregation.

In the research program on dust characterization it was thought that the most important factor in hard rock mines might be the size distribution of the quartz component of the respirable size fraction of the airborne dust. The development of the direct-on-filter technique for quartz assessment of routine dust samples led to the consideration of size- selective multi-sampler systems each with a different size cut so that the samples could be assessed for quartz with the existing simple technique. Originally this ten-sampler train was developed using horizontal-elutriator size selectors(8). This system though excellent in laboratory use

was very clumsy for underground mines. The unit was rebuilt using multistage impactor size selectors(9).

Our experience demonstrated that the experimental and theoretical equations developed by others could be successfully applied but that there were two major restrictions on design. These are:- firstly, that minimum separations between orifices are required to avoid unexpectedly high secondary deposition; and secondly, that the dust loading on each stage must be low.

The minimum separation between orifices required is a major limitation in designing compact impactor size selectors. We have taken an alternative approach which accepts that secondary deposition will occur and calibrate complete samplers against a reference sampler adjusting the air flow until they both indicate the same respirable dust concentration in a poly-disperse dust cloud(1).

As the dust piles under each orifice increase in height and approach the exit of the orifice, secondary dust deposition increases and some dust is re-entrained from the pile. On balance it appears that the dust penetration decreases at first with increasing load and increases at higher dust loadings. It has been found that the use of previous stage(s) to reduce the dust loading on the final stage can greatly reduce this problem.

This report describes the development of four sampling systems using impactor size selectors;-

1. The CAMPEDS 2 litre/minute flow rate sampling head.
2. The CAMPEDS improved 4 litre/minute sampling head.
3. The high flow rate sampling head.
4. The size distribution analysis train using 10 sampling heads with different cut-offs.

THE CAMPEDS 2 LITRE/MINUTE SAMPLING HEAD

The CAMPEDS dust sampling and assessment system was developed using the most suitable dust sampler available on the market(1,2). The Cassella personal sampler cyclone was chosen as it collected about twice as much dust as the samplers based on the 10mm nylon cyclone and the plastic filter holders. Later development of the nylon cyclone,such as the use of airflow pulsation dampers and metal filter holders, reduced the difference to about a factor of 1.5. The 25 mm diameter filter was also a major factor in increasing the X-ray response to the quartz in the direct-on-filter method developed. This sampling system used

TABLE 1 CALIBRATION OF 2 litre/min CAMPEDS

Orifice Diameter mm		Indicated respirable dust concentration relative to that of the 113A
First	Second	
NU*	4.4	1.68
NU	3.2	1.68
NU	2.5	1.5
4.4	4.1	1.34
4.4	3.8	1.28
4.4	3.2	0.93
3.8	3.2	0.88
3.8**	3.5**	1.00

Footnotes

* Not Used

** Selected Values

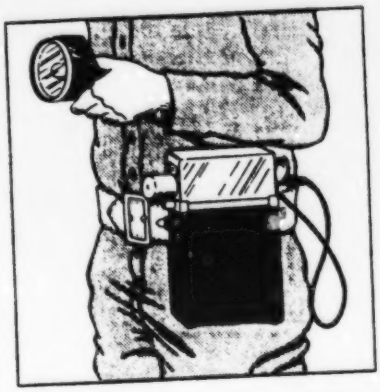
a pump and sampling head mounted on the cap-lamp battery because it was shown to be more robust and simpler to issue in underground mining conditions. It also showed promise of being amenable to self issue when lamp usage discipline is maintained and an off-charge operated switch is introduced.

Mr Jacobsen's proposal of using a pressed plastic filter holder and impactor size selector looked promising(5,6). A layout suitable for mounting on the pump cap-lamp battery unit was designed. The first single stage unit was shown to undersample respirable dust at dust loadings above 0.5mg of dust collected(1). The addition of a preliminary impactor stage to decrease the amount of dust collected at the main impactor size selector appeared to eliminate this problem up to the equivalent of the maximum dust collection attainable with the reference dust sampler, about 2mg of respirable dust on the filter. Later field work showed nonlinearity with the cyclone in comparisons at high dust loadings(10). Further laboratory work showed that the dust penetration through the impactor started to decrease relatively at coarse dust collections of about 5 mg. In this study, in which consecutive samples were taken with up to three reference samplers, it was shown that the Casella and the nylon cyclone samplers were linear and that the impactor samplers departed slightly at high dust loadings.

The layout of the sampling head is shown in fig. 1 , the size selection calibration is given in table 2 and the orifice characteristics are given in table 2.

The major features of the dust sampling head are:-

1. The reproducibility of size selection performance using drilled holes.
2. The two stage size selector to increase coarse dust holding capacity.
3. The use of adhesive, petroleum jelly, on the impaction surfaces to increase coarse dust retention.



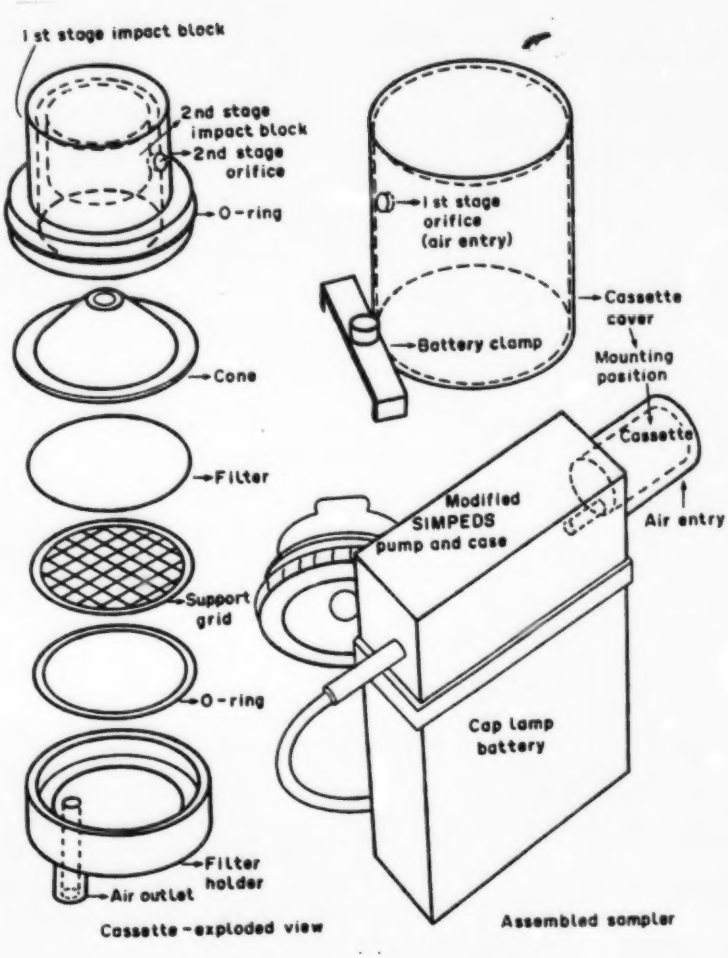


Fig. 1 The CAMPEDS 2 l/min Personal Dust Sampler

Table 2 Orifice characteristics of the three Impaction size selectors

	Pitch circle mm	Orifice diameter mm	Impact Height mm	Number of orifices	Airflow per section l/min	Theoretical 50% cut μm
CAMPEDS 2 litre/min sampler						
Entry	NA	3.8	entry velocity = 2.5 m/sec			
1st stage	NA	3.8	6	1	2.0	6.3
2nd stage		3.5	4	1	2.0	5.95
CAMPEDS 4 litre/min sampler						
Entry	0	6.4	entry velocity = 2 m/sec			
1st stage	0	6.4	8	1	4.0	10
2nd stage	24	2.2	3	4	1.85	6.18
	24	1.3	3	8	1.292	4.35
	24	0.8	3	14	0.856	3.75
High volume 20 l/min sampler						
Entry	0	10.6	entry velocity = 2 m/sec			
1st stage	0	10.6	12	1	20	10
2nd stage	38	2.8	2.5	10	8.8	6.45
	38	1.7	2.5	20	6.3	5.1
	27	0.9	1.5	54	4.9	3.65

4. The labyrinth seal between the coarse dust collection zone and the respirable dust filter to minimize coarse dust carryover on handling.

5. The use of an entry cone to spread the dust over the respirable dust filter surface.

6. The use of a combined size-selector filter-holder cassette for filter transport and dust collection.

7. The use of an elastomeric O-ring and spring loaded cassette mounting to seal the filter assembly without requiring much operator training and experience. As many as 30% of filters from mines using nylon cyclones have shown evidence of poor sealing when new technicians start(11,12).

THE CAMPEDS 4 LITRE/MINUTE SAMPLING HEAD

It was appreciated that the 2 litre/minute CAMPEDS impactor could be expected to have a very sharp cutoff because of the two close stages. The paper by Marples and McCormack suggested an approach which could give a cutoff shape closer to the respirable dust specification(7). Their approach, using sets of orifices of different sizes with the same pressure drop across, them seemed promising. However, their requirement of equal airflow through each set appeared to be an unnecessary restriction and was dropped. It was also

apparent that a sampler with a higher flow rate would be useful in the generally lower dust concentrations now prevalent in the mines and the expected decrease in permissible dust concentrations following the recommendations on permissible exposures to quartz dust(14). It was also appreciated that sampling pumps had improved since the development of the 2 litre/minute sampler and would support a higher flow rate for a full 8 hour shift in most situations in hard rock mines.

The concepts adopted in the design were :-

1. The filter and internal body diameter would be 25mm.
2. The coarse dust collection surface would be an oil soaked sintered metal sheet(15).
3. The coarse dust collection surfaces would lie in one plane.
4. The oil soaked coarse dust collection component would be mounted within a weighable assembly to enable assessment of total dust with the sampler.
5. The second stage impactor sets of orifices would be designed to match the British Medical Research Council respirable dust specification (16,17).
6. The first stage impactor orifice would be set to approximate the entry air velocity most commonly used in Europe for total dust sampling.
7. The sets of second stage orifices would be drilled in a single component surrounding the entry jet.
8. The design flow rate for the second stage orifices would be over 4 l/min with the expectation that the cramped space would lead to secondary deposition. Equal 'respirable dust' concentration to the reference dust sampler was expected to be achieved at a flow rate close to 4 l/min.
9. The alternation of large and small orifices apparently showed least secondary deposition and was used.

A theoretical study showed many possible designs. The most flexible in matching any specific selection curve was obtained using only one orifice of each size. The design was built up from the coarse end and required reiteration to get a good match. However, this was a complex design to fabricate and it was not constructed. The final design used three sets of second stage orifices as described in table 2.

The sampling head is shown in figures 2and 3. The results of calibration are shown in table 3. Field tests have demonstrated the usefulness of the higher flow rate and resultant greater dust collection(18,19).

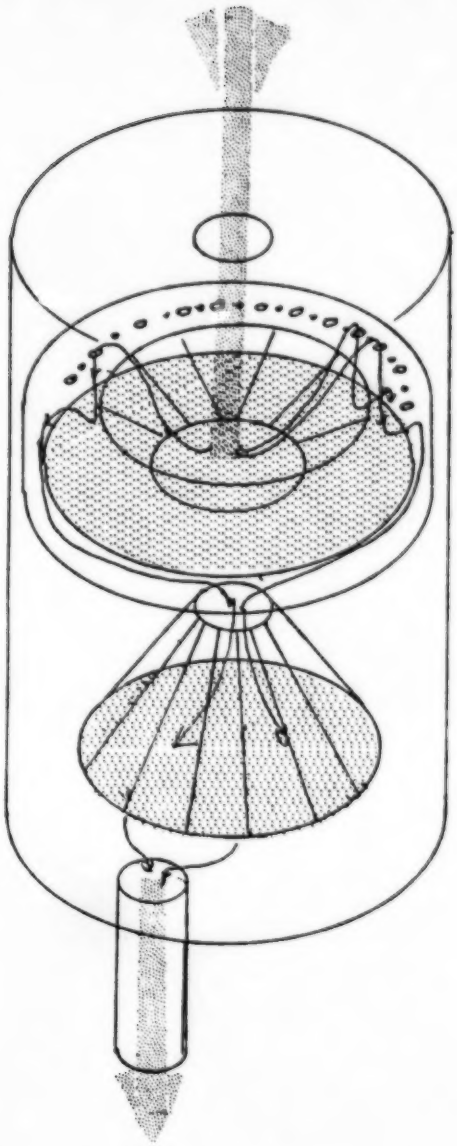


Fig. 2 Schematic of CAMPEDS 4 l/min Personal Dust Sampler

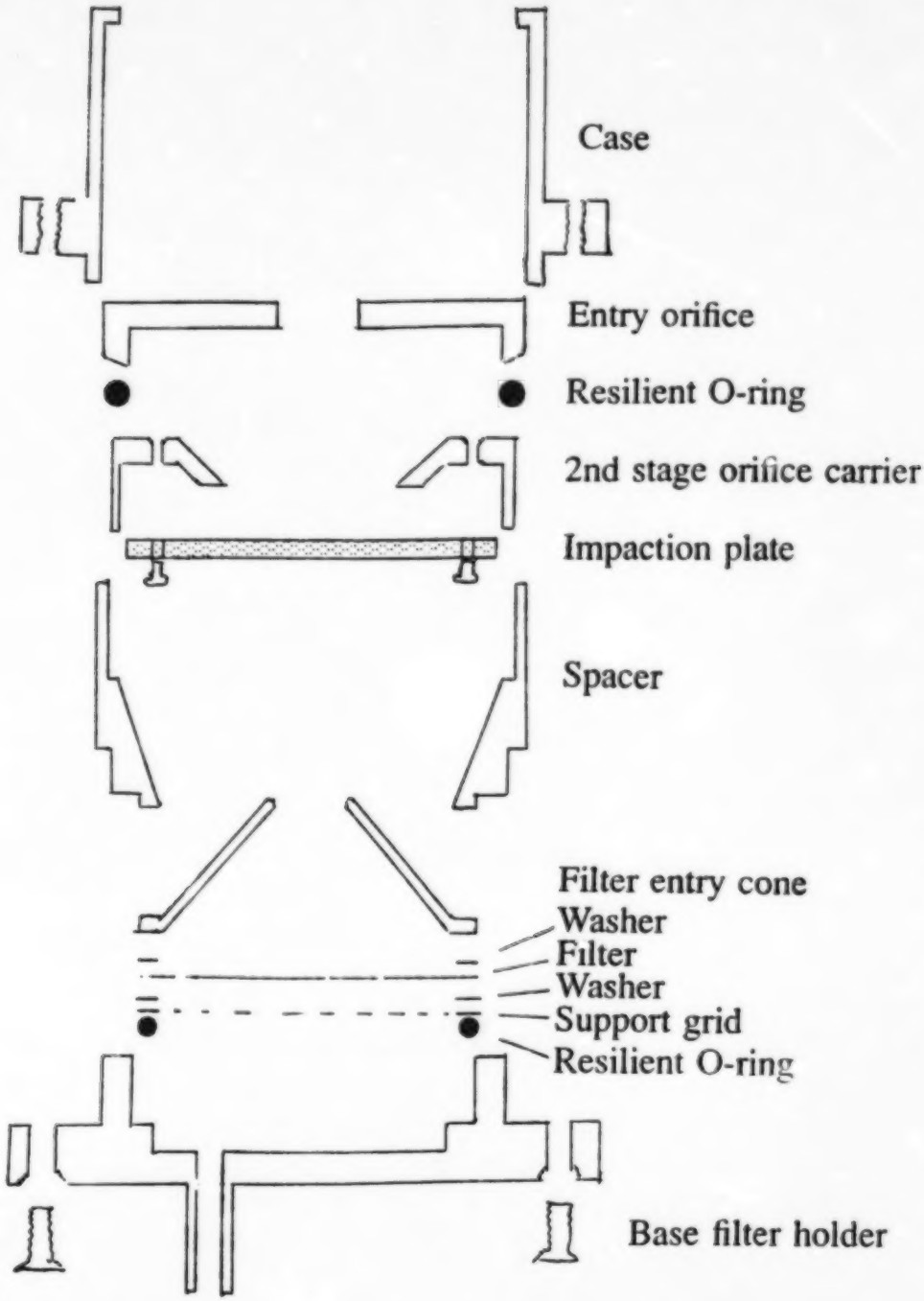


Fig. 3 Assembly and Components of CAMPEDS 4 l/min Sampler

The axis is vertical and most components are radially symmetrical

Table 3 calibration of 4 litre/min CAMPEDS sampler

Run	Dust collected, mg, by sampler at given flow rate in l/min							
	4.0		3.67		3.33		3.0	
	mg	ratio*	mg	ratio	mg	ratio	mg	ratio
1	1.94	0.97	2.02	1.09	1.92	1.15	2.06	1.37
2	2.70	0.98	2.75	1.10	2.78	1.23	2.74	1.35
3	2.18	1.00	2.27	1.13	2.19	1.21	2.15	1.32
4	2.08	1.01	2.11	1.12	2.11	1.23	2.10	1.31

Footnote

* Ratio of indicated respirable dust concentration to that given by the reference respirable dust sampler. (the Hexhlett)

THE HIGH VOLUME SAMPLING HEAD

In the early stages of the study on long lived radionuclides in airborne dust it was considered that sensitivity could be a problem. The counting equipment would accept a 47 mm diameter filter and the objective was to design a respirable dust sampler with a maximum attainable flow rate. The same design criteria were used as in the 4 l/min sampler above. The required flow rate could be controlled by available critical orifices and there were both 120 volt AC electrical and compressed air powered suitable sources available in the laboratory to achieve the required suction. The prototype sampler was designed for a 50 l/min airflow and on calibration was found to agree with the reference respirable dust sampler at 30 l/min.

Field and laboratory experience showed useful results with the prototype sampler. However, it was found that there was a lot of secondary deposition which led to difficulties in assessing the coarse non-respirable fraction of the dust. It was thought desirable to reduce this and a reduction in flow rate was proposed. The orifice diameters were reduced to give theoretical agreement with the BMRC specification at 25 l/min. The sampler is similar in design to the 4 l/min CAMPEDS with the exception of the 2nd stage orifice carrier which is large enough for two rings of second stage orifices. The orifice characteristics are shown in table 2.

G. Knight's move to Ottawa prevented his completing the development. Field tests demonstrated that the prototype sampler produced plenty of dust in a short sampling period for both gravimetric and long lived radionuclides assessment. These tests were carried out during other studies but not reported(18,19).

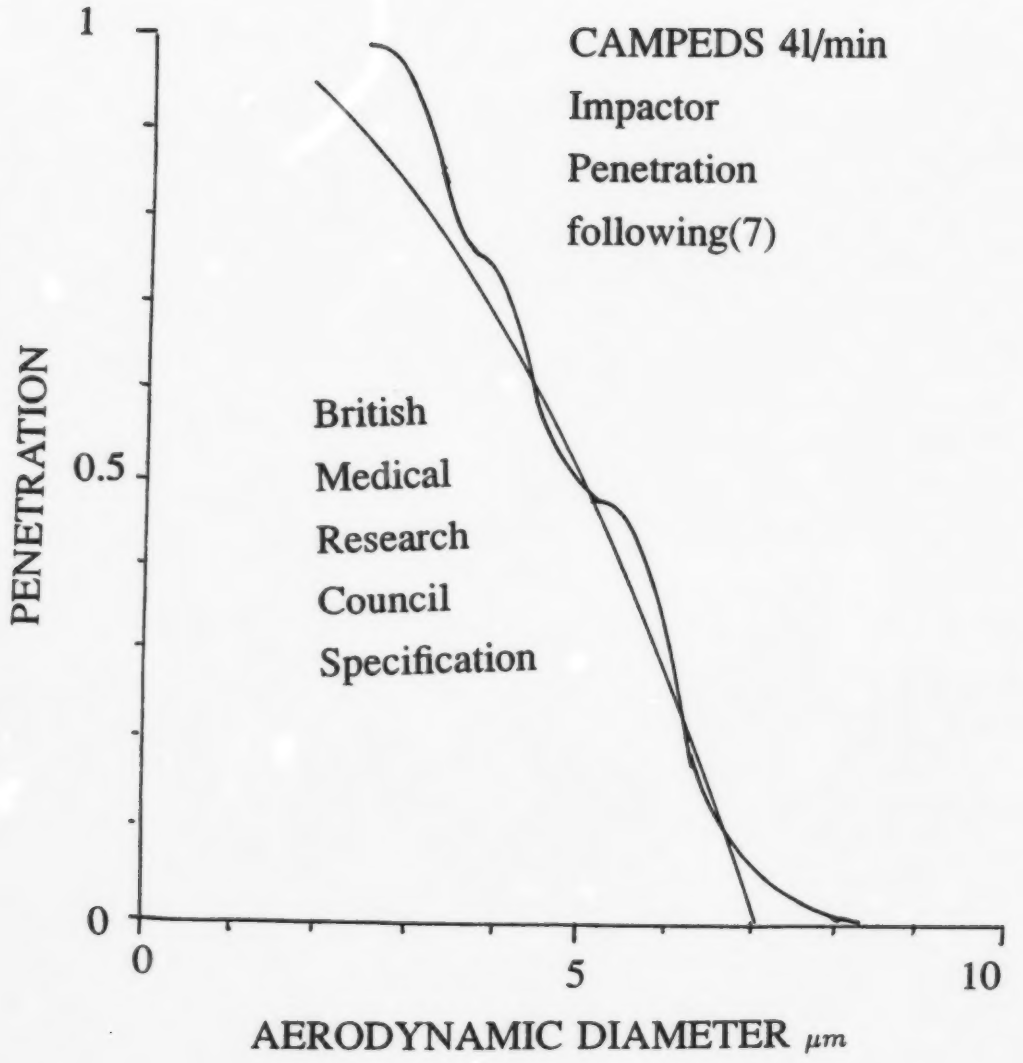


Fig. 4 Penetration through the 4 l/min size selector-following Marples Treatment

SIZE DISTRIBUTION ANALYSIS TRAIN

The size distribution analysis sampling train's main objective was to provide dust samples suitable for direct-on-filter analysis of quartz using X-ray diffraction. The original sampling train used horizontal elutriator size selectors with differing ratios of airflow to floor area to cover the desired size range(8). Horizontal elutriators were used because of the easy theoretical calculation for the size cut, and the expectation that the theoretical performance would be met in practise. The train performed well in the laboratory but was too clumsy and had too low a flow rate for field use. Impactors were first designed and built to replace the largest elutriators, those with a fine size cut. It was found that some factors were desirable for good performance in a limited size package; these were:-

1. The minimum diameter orifice desirable is 1 mm. Fine orifices can be partially obstructed with adhesive and dust during cleaning and preparation.
2. The final stage of the finer size selectors was designed using the number of 1mm diameter orifices required to meet the chosen 50% cut.
3. The final stage was preceded by multiple stages to reduce the dust loading on each stage. An overloaded impaction stage shows secondary dust deposition in lines and streaks between the individual piles of dust under each impaction orifice when a dark dust such as coal is collected.
4. The orifices were placed on large and small pitch circles alternating between stages. No more than six orifices were used on the smallest pitch circle. Up to 16 orifices were used on the larger pitch circle.
5. The impact height was set to about one and a half times the orifice diameter.
6. The airflow was increased as the size cut was decreased to maintain a more or less constant dust collection on each filter.
7. The maximum airflow through a 25mm diameter filter is about 15 litres/ minute and the highest flow rate used is 10 litres/ minute.
8. A flow rate of 2 litres/ minute is used for the total and coarse cut dust samplers.
9. Intermediate flow rates are used for the intermediate size cut samplers.
10. Duplicate respirable dust samples are collected and the concentration used as a normalising origin in plotting and describing size distributions.

The construction outline of the samplers is shown in figure 5 and the details of the impact stages for each sampler in table 5. The airflow for each sampler is controlled by a

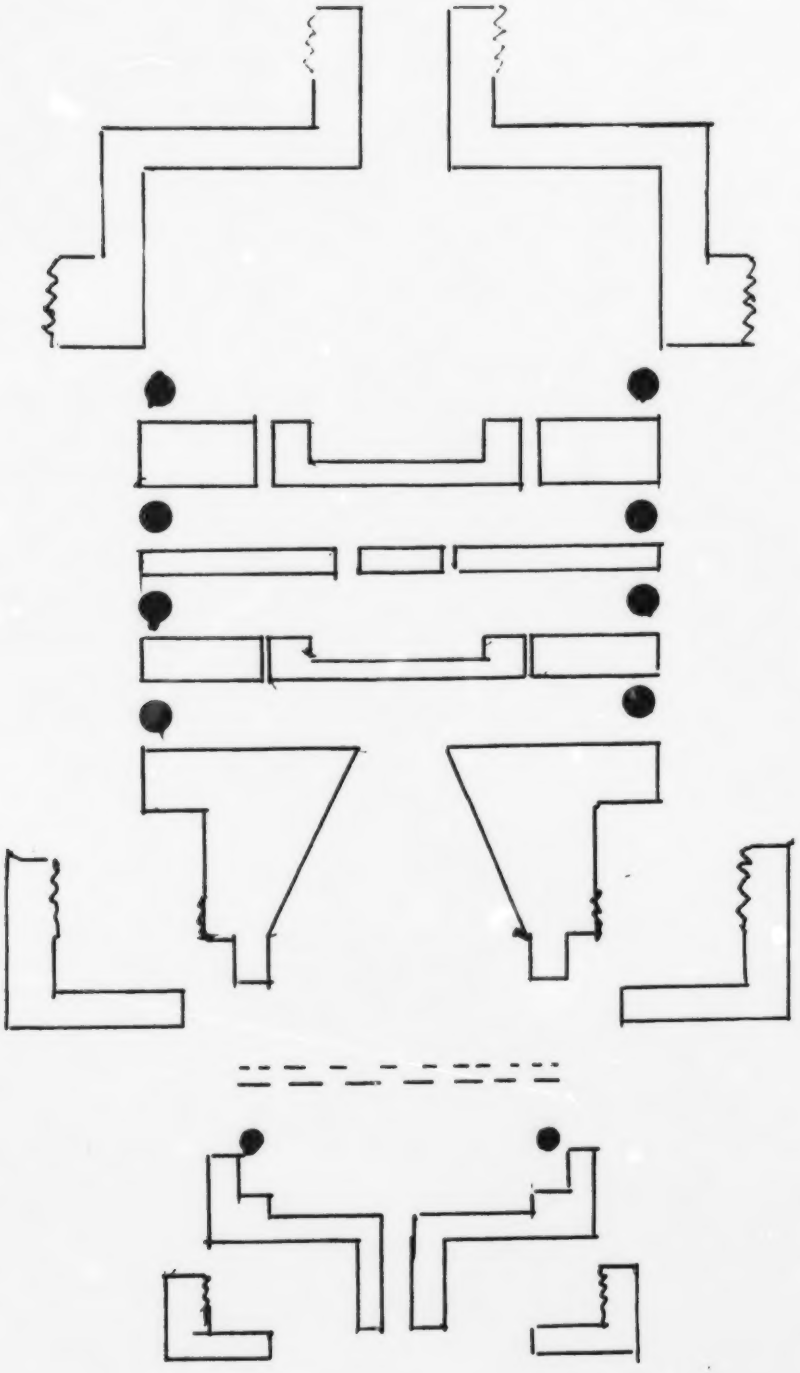


Fig 5 Layout and components of one sampler from S.D. train.

Table 5 orifice characteristics for the size distribution train

	Pitch circle mm	Orifice diameter mm	Impact Height mm	Number of orifices	Airflow per section l/min	Theoretical 50% cut μm
Number 1 Total dust sampler						
entry	0	4.6		1	2	
Impactor 2 design cut 11.5μm						
stage 1	0	6	6	1	2	12.5
stage 2	16	2.3	2.5	12	2	11.5
Impactor 3 design cut 6.4 μm						
stage 1	0	4.6	6	1	2	9
stage 2	16	1.6	2.5	12	2	6.4
Impactors 4 and 5 duplicate respirable dust samplers						
stage 1	0	5.3	8	1	2.7	9.5
stage 2	16	1.6	2	12	2.7	5.5
stage 3	8 + 0	1.9	2.5	7	2.7	5.4
stage 4	16	1.6	2.	8	2.7	4.5
Impactor 6 design cut 3.32 μm						
stage 1	0	6.5	9	1	4	10.5
stage 2	16	1.5	2	12	4	4.1
stage 3	28	1.3	2	16	4	3.85
stage 4	18	2.0	3	4	4	3.65
stage 5	28	1.3	2	12	4	3.32
Impactor 7 design cut 2.8μm						
stage 1	0	8.6	10	1	7	12.5
stage 2	18	2.5	3	8	7	5.5
stage 3	28	1.5	2	16	7	3.6
stage 4	18	1.9	3	6	7	3.15
stage 5	28	1.4	2	16	7	3.2
stage 6	18 + 0	1.7	2.5	7	7	2.88
stage 7	28	1.6	1.5	8	7	2.8

TABLE 5 Continued

	Pitch circle mm	Orifice diameter mm	Impact Height mm	Number of orifices	Airflow per section l/min	Theoretical 50% cut μm
Impactor 8 design cut 1.8μm						
stage 1	0	10	10	1	10	12
stage 2	28	1.6	3	16	10	3.3
stage 3	18 + 0	1.6	3	13	10	3.0
stage 4	28	1.4	2	16	10	2.72
stage 5	18	1.9	3	6	10	2.63
stage 6	28	1.6	2	8	10	2.33
stage 7	18	1.6	2	6	10	2.03
stage 8	28	1.4	1.5	7	10	1.92
Impactor 9 design cut 0.94μm						
stage 1	0	10	10	1	10	12
stage 2	28	1.7	3	16	10	3.55
stage 3	18	2.1	3	6	10	3.03
stage 4	28	1.4	2	16	10	2.72
stage 5	18	1.8	3	6	10	2.42
stage 6	28	1.3	2	12	10	2.1
stage 7	18	1.2	2	8	10	1.48
stage 8	28	1.0	1.5	10	10	1.3
stage 9	18	1.0	1.5	8	10	1.17
stage 10	28	1.0	1.5	5	10	0.94
Impactor 10 design cut 0.73μm						
stage 1	0	10	10	1	10	12
stage 2	28	1.7	3	16	10	3.55
stage 3	18	2.1	3	6	10	3.03
stage 4	28	1.4	2	16	10	2.72
stage 5	18	1.8	3	6	10	2,42
stage 6	28	1.3	2	12	10	2.1
stage 7	18	1.2	2	8	10	1.48
stage 8	28	1.0	1.5	10	10	1.3
stage 9	18	1.0	1.5	8	10	1.17
stage 10	28	1.0	1.5	5	10	0.94
stage 11	18	1.0	1.5	4	10	0.84
stage 12	28	1.0	1.5	3	10	0.73

critical orifice with a vacuum gauge indicator and a valve to maintain the inlet pressure to the critical orifice at the calibrated value. The valve is adjusted to allow for the build up of pressure drop as dust is deposited on the filter. The impaction size selectors were compared with horizontal elutriators in a pure freshly prepared mineral dust cloud in the laboratory dust chamber. It was found that the horizontal elutriators can be made to lie on the size distribution curve plotted from the impactors with only a very slight displacement along the size axis. The impactors give slightly less dust probably due to greater cut given by the preceding multi-impactor stages on each sampler. It is presumed that the agreement between the theoretical and practical is closer for the elutriators than for the impactors, and thus an equivalent elutriator 50% cut is derived from this comparison for each impactor sampler.

Table 6 shows the calibration of the X-ray diffraction for quartz analysis when using the size distribution train. It can be seen that the calibration is similar for the coarse samplers but becomes very much less sensitive for the finest size. It is presumed that this is due to the small size effect which has been reported before. Note, however, that it is not significant for most of the respirable dust size range.

Table 6 Calibration of size distribution sampling train for quartz analysis

Sampler	Ratio of quartz weight to XRD intensity * for diffraction line (Miller indices)			
	1,0,0	1,0,1	1,1,2	2,1,1
1-total	1.15	1.07	1.29	1.22
2-11.5μm	1.23	1.11	1.29	1.23
3–6.4μm	1.15	1.05	1.29	1.25
4& 5-5μm	1.16	1.03	1.29	1.27
6–3.3μm	1.10	1.13	1.40	1.39
7–2.8μm	1.14	1.10	1.36	1.38
8–1.9μm	1.19	1.24	1.57	1.60
9–0.9μm	1.52	1.60	1.12	2.32
10-0.7/mum	4.36	3.47	5.10	4.99

Footnote

* XRD intensity expressed as mg quartz equivalent as calibrated using the CAMPEDS 2 l/min sampler. All samples collected in a pure quartz dust cloud.

Experience with this sampling train has not found significant differences in the size distribution of the respirable size fraction in mining situations. The total respirable dust is variable as is to be expected from the variable ratio between dust from the two major sources, fine soot from diesel engine exhaust and relatively coarse dust from mineral handling. As expected, the coarse non-respirable fraction varies greatly.

DISCUSSION

The dust samplers using impaction size selectors that have been designed and built in the Elliot Lake Laboratory have been described in this report. Note the production prototypes and the production version of the 2 l/min CAMPEDS dust sampler were built in the Massey Machine Shop by its owner Mr. P. Pike. It has been shown that impaction samplers are flexible in design and layout leading to compact light weight samplers. These samplers are very robust mechanically, with respect to reproducibility of performance and to avoidance of coarse dust transfer to the respirable dust section during wear and handling. In all these respects the CAMPEDS 2 l/min sampler was preferable to the cyclone based size selectors tested. In only only one aspect were the cyclone based samplers superior. This was linearity when collecting large quantities of coarse dust, over 5mg. Multistage samplers were shown to have a much greater coarse dust holding capability and two or more stages have been a feature of the this laboratory's designs. There is a possible problem if fine orifices are used, less than 1.5mm in diameter, in that they are prone to partial obstruction by mixed adhesive and dust during cleaning and preparation. During the development it seemed that multi-orifice stages had a greater dust holding capacity than a single orifice stage with the same flow rate and size cut. However, if it is assumed that the dust holding capacity of the impact plate under an orifice is proportional to the area of the orifice times the height (separation between orifice and impact surface). Then, as the height is approximately proportional to orifice diameter the dust holding capacity should be proportional to $n.d^2.h$ or $n.d^3$. The size selection factor is proportional to $n.d^3/flow$. Thus one would expect the dust holding capacity of a stage to be independent of the number of orifices in it.

There appears to have been a close match between expected and practical performance of impactor size selectors but it is considered to be essential to calibrate them by comparison with a reference dust sampler with known characteristics because of two effects. Secondary dust deposition is difficult to avoid completely and thus its effect on size selection is not known. Also, the shape of the size selection curve is not a perfect match to the respirable size selection curve and it is difficult to select the optimum flow rate for the best match. A better agreement with a reference respirable dust sampler can be obtained by comparison in a polydisperse dust cloud and adjustment of airflow(20) as a calibration procedure.

It has been shown possible to modify the rather sharp size cut of impactor size selectors to give a better match to the shape of the respirable dust specification by using multiple orifices of different sizes in the final stage of the respirable dust sampler but this adds greatly to the complication of building them and probably gives rise to greater difficulty in maintenance because of the small orifices required. In view of the excellent performance of the single orifice per stage 2 l/min CAMPEDS sampler in laboratory and field comparisons it is suggested that such elaboration is of little merit in most industrial situations where polydisperse dust clouds are the norm(10).

The major conclusion of experience with impactor size selector samplers is that their design is flexible, they are robust and can give a very good performance.

REFERENCES

1. **Knight, G.:** Mine dust sampling system–CAMPEDS. *CANMET report 78-7* CANMET, Energy Mines and Resources, Canada. Ottawa (1978)

2. **Knight, G.:** CAMPEDS– a dust sampling and assessment system for use in hard rock mines. *Ann. Occup. Hyg. 30(2)*: 139-151 (1986)

3. **Higgins, R.I. and P. Dewell:** A gravimetric size selecting personal dust sampler. In *Inhaled particles and vapours* edited by C.N. Davies. Oxford: Pergamon Press (1967)

4. **Casella:** *Manufacturer* London. U.K.

5. **Jacobsen, M.:** Personal communication (1974)

6. **Tomb, T.F. and H.N. Treaftis:** A new two-stage respirable dust sampler. *Am. Ind. Hyg. Assoc. J. 36(1)*: 1-9 (1975)

7. **Marple, V.A. and J.E. McCormack:** Personal sampling impactor with respirable aerosol penetration characteristics. *Am. Ind. Hyg. Assoc. J. 44(12)*:916-922 (1983)

8. **Knight, G.:** A simple method for determining size distribution of airborne dust by its settling velocity. *Am. Ind. Hyg. Assoc. J. 33(8)* : 526-532 (1972)

9. **Knight, G., E. Moore and C.W. Smith:** Size distribution of dust in Labrador iron mines *Am. Ind. Hyg. Assoc. J. 48(2)*: 150-154 (1987)

10. **Knight, G. and E. Moore:** Comparison of dust samplers for use in hard rock mines. *Am. Ind. Hyg. Assoc. J. 48(4)*: 354-363 (1987)

11. **Frazee, P.R. and G. Tironi:** A filter cassette assembly method for preventing bypass leakage. *Am. Ind. Hyg. Assoc. J. 48(20)*: 176-180 (1987)

12. **Knight, G.:** in letters to the editor *Am. Ind. Hyg. Assoc. J. 48(6)*: p. A-392 (1987)

13. **Carson, T.P., S.S. Shulman and C.D. Lorberau:** An investigation of the performance of the 10-mm nylon cyclone. *Appl. Ind. Hyg. 2(2)* : 47-52 (1987)

14. **National Institute for Occupational Safety and Health:** *Criteria for a recommended standard....Occupational exposure to crystalline silica* (DHEW/NIOSH Pub. No. 75-120) Washington, D.C.: Government Printing Office, 1974

15. **Reischl, G.P. and W. John:** The collection efficiency of impaction surfaces: a new impaction surface. *Staub Reinhalt. Luft 38*: 55 (1978)

16. **(British) Medical Research Council:** In *Inhaled particles and vapours*, edited by C.N. Davies. Oxford: Pergamon Press, 1961. p.475

17. **Anon:** In *Proceedings of the pneumoconiosis conference, Johannesburg,* edited by A.J. Orenstein. London: J. and A. Churchill, 1960. p. 620

18. **Knight, G. and S. Hardcastle:** Efficiency tests on a wet dust collector in a hard rock mine. *Mining Research Laboratories, Div. Rep. 87-95(TR).* Ottawa. CANMET, Energy, Mines and Resources, Canada, 1987.

19. **Knight, G.:** Dust production at an ore and waste dump area in an underground uranium mine. *Mining Research Laboratories, Div. Rep. 87-58.* Ottawa. CANMET, Energy, Mines and Resources, Canada, 1987.

20. **Knight, G.:** A reference size selective sampler for respirable dust. *Mining Research Laboratories, Div. Rep. 87-17(J).* Ottawa. CANMET, Energy Mines and Resouces, Canada, 1987